Effective monitoring and control with intelligent products

Meyer, Gerben Gerald

Part II

Monitoring and Control in Production

Chapter 3

System Architecture for Production

Advances in production planning and control in recent decades have focused on increasing the sophistication of the planning function. For good reasons, these advances have led to the centralisation of the planning function in production. However, centralised planning and control has drawbacks concerning monitoring and control, due to the many small disturbances that occur. Monitoring and control are by their nature decentralised, beginning on the shop floor, and, therefore, the desire for greater sophistication in monitoring and control leads to renewed interest in decentralised and localised approaches. This chapter demonstrates a system architecture for decentralised production monitoring and control based on the concept of intelligent products. Intelligent products are aware of their local context and can negotiate with local manufacturing resources if needed. As such, local solutions to problems can be proposed directly when problems occurs. With the advancement of the Internet of Things, such a scenario is likely to become feasible in the near future.[1]

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3.1 Introduction

This chapter presents a new architecture for a monitoring and control system in the context of Production Planning and Control (PPC). PPC is concerned with reconciling the demand and the supply of products and materials in terms of volume, timing and quality. The activities required to achieve this are typically clustered into four broad functions: (1) loading, (2) sequencing, (3) scheduling and (4) monitoring and control [166]. The first three collectively constitute the production planning function; the fourth the production control function. Advances in PPC over recent decades have mainly focused on increasing the sophistication of the production planning function. This has steadily resulted in centralised PPC activities.

There are good reasons for centralising the loading, sequencing and scheduling activities. From a materials perspective, centralised coordination of the supply chain reduces the bullwhip effect [89, 114], by using appropriate rules for safety stocks and lot sizes. In addition, centralised coordination can solve the problems of matching sets of parts and balancing the supply streams of all components in an assembly's bill-of-material [136]. From a capacity perspective, optimising one resource will usually have an impact on other resources. Given this situation, some form of coordination is not only useful but virtually unavoidable.

Monitoring and control cover the activities performed in order to react to disturbances. These activities may lead to deviations from the original plan [166]. The vast majority of academic effort into PPC has been spent on the more sophisticated planning concepts, while monitoring and control has received much less attention [187]. However, planners in real life devote most of their efforts to monitoring and controlling, rather than carrying out planning activities [69, 118, 143]. This justifies a renewed interest in monitoring and control.

Centralised planning and control can have drawbacks concerning monitoring and control (see e.g. [171]). Drawbacks appear due to the many small disturbances that occur. A well-known example is when a component is damaged just before it is needed in manufacturing. This is especially problematic in case of production of highly customised products, where buffer stocks are typically small or even non-existent, due to expensive components or order-dependent customisation. The damaged component must be repaired, or a similar component has to be sourced from elsewhere, in order to continue with the original plan. Often, these minor disturbances are not even made known to the central planners, and are simply solved at a more local level by the shop floor supervisor. Other examples of disturbances are production errors, machine failures, quality problems and shipment errors. As will be discussed in detail in Section 3.3, centralised planning and control systems typically have problems in handling with such disturbances, due to the applied aggregation and the hierarchical nature of these systems. The advancement of the Internet of Things however enables new system designs which might address these problems.

Based on these arguments, a new design approach for a monitoring and control system is presented in this chapter. The main goal of this approach is to enable new ways in which disturbances can be dealt with, in order to increase the robustness of the overall plan execution. To investigate the potential of the proposed system design, computer simulations have been performed, which are described in detail in the next chapter. In the various simulation runs, several existing hierarchical and centralised planning and control systems will be compared to the approach presented here. The usual measures of performance in PPC studies are based on financial results (see e.g. [34]). However, profit as the main measure of performance does not give sufficient weight to the impact of disturbances. Our fundamental observation is that studies focusing on production planning performance tend to ignore small disturbances, although these, in reality, dominate the planner's activities in practise. Therefore, robustness is proposed here as an important additional measure of performance of a monitoring and control system.

This chapter is structured as follows. Section 3.2 will elaborate on the background and related work. Next, Section 3.3 will define the problem statement, based on an analysis of the problem area. Afterwards, the new architecture for a monitoring and control system will be presented in Section 3.4. The chapter ends with conclusions.

3.2 Background and related work

3.2.1 Centralisation versus decentralisation of PPC

The roots of production planning and control reside in decentralised approaches. In the years following the Second World War, authors such as Magee [110] approached production planning and inventory control as two separate problem areas. In academia, authors such as Conway et al. [37] studied job shops using queueing theory. In these earlier times, the focus was on simple rules to support decentralised decision-making.

Centralised production planning and control became the dominant paradigm when computers entered the scene, especially because computers could maintain interrelated time-phased plans for the flow of goods (leading to inventory control based on "time-phased order point"). Based on early experiences with the time-phased order point concept, authors such as Orlicky [136] advocated Material Requirements Planning (MRP I) as the panacea for problems related to production planning and control.

However, MRP I turned out to be based on many assumptions, such as batch manufacturing, production to stock and a stable master schedule, which limited its applicability. Therefore, MRP I evolved into MRP II, which is a hierarchical framework for PPC rather than just a material planning algorithm. However, the focus with MRP II remained on providing decision support to the master planner and the material planner, rather than offering innovation in monitoring and control. Although the claims for MRP II have been challenged by authors writing about Just-in-Time production [64, 161], Optimised Production Technology [61] and customer-driven manufacturing (see e.g. [199]), most current approaches continue to reflect the centralised and hierarchical nature of MRP II with little focus on monitoring and control. In these approaches, monitoring and control are typically implemented through decentralised Manufacturing Execution Systems (MES) [113]. These MES deliver work-order progress transactions to the PPC systems. However, the advancement of MES does not change the centralised and hierarchical nature of the PPC systems. The technological change in information systems, from client-server technology to Advanced Planning Systems (APS), has also not changed the focus on decision support in central planning systems [198]. Lean manufacturing does, however, take a slightly different position (see e.g. [159]). The main scheduling principle in lean assembly is Hejunka scheduling, in which material flows are balanced. Although this principle is a concept within central planning, the Kanban system can be interpreted as a system of decentralised monitoring and control. In this respect, lean manufacturing is an exception to the rule that central planning concepts tend to neglect monitoring and control.

3.2.2 Distributed monitoring and control

Monitoring and control of manufacturing equipment and automated control of manufacturing steps have made great progress in recent decades. In general, the term intelligent resources is used to indicate manufacturing resources in modern factories that are being able to execute and control manufacturing activities, as well as being capable of monitoring and controlling their own status [160]. Process quality parameters are monitored, such as tolerances in mechanical machinery, or pressures and temperatures in chemical equipment.

Many authors consider agent encapsulation as the most natural way to make resources intelligent (see e.g. [24, 150, 185]). In this context, an agent is defined as a software system that communicates and cooperates with other software systems to solve a complex problem that is beyond the capability of the individual software systems. Intelligent resources can react to manufacturing problems and investigate alternative machines and routes for products on the shop floor in the event of disturbances. Another approach is holonic manufacturing, in which a holon is defined as an autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects [74, 103].

Although individual resources are becoming more intelligent and autonomous, integrating various intelligent resources has remained cumbersome due to their dedicated and propriety nature. In order to achieve interoperability among the various autonomous intelligent resources, an open, flexible and agile environment with "plug-and-play" connectivity is seen as essential [83]. As such, there is an increased interest in developing architectures

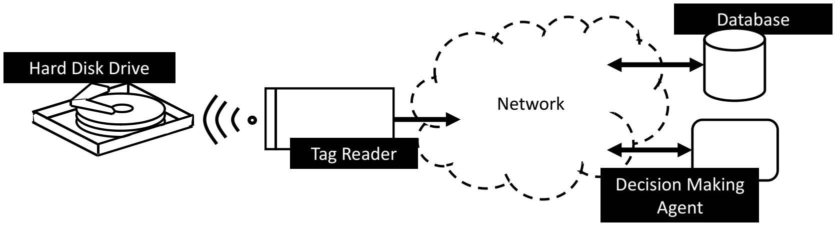


Figure 3.1: Intelligent Hard Disk Drive (derived from [195])

that enable a more generic integration between intelligent resources. An example is the SOCRADES project, in which a device-level Service-Oriented Architecture for factory automation is being developed [179]. Furthermore, there is increasing interest nowadays in applying intelligent products and the Internet of Things in manufacturing and supply chain management, as described in Chapter 2. McFarlane et al. [116] define an intelligent product as a physical and information-based representation of a product. This is the basic principle behind the Internet of Things: all everyday devices will be enabled to connect to a data network [59]. Figure 3.1 provides an example of a hard disk drive as an everyday device connected to a data network. A decision making agent is attached to provide the intelligence.

It is likely that in the future not only resources but all items and devices on the shop floor will become intelligent due to advancements in intelligent products and the Internet of Things. The interoperability between all these connected devices will be provided using the same data protocols that are currently used for the Internet [45, 58]. Therefore, the challenge is to determine how one can create manufacturing systems involving many intelligent items and resources that can work together and adapt to changes both on the shop floor level as well as on a factory-wide basis. This work anticipates on these future developments.

3.3 Problem analysis

3.3.1 Analysis

The term monitoring and control needs elaboration in the context of a discussion about aggregation. Aggregation is widespread in PPC (see e.g. [8, 156]). The first observation is that most centralised systems aggregate over time. These systems perform loading, sequencing and scheduling tasks in aggregated time periods of months, weeks, days or even shifts. As such, these systems are unable to identify sequencing problems within these periods. Secondly, centralised planning systems aggregate by location. Materials issued to the shop floor are booked as work-in-progress, but no information is available on where on the shop floor these materials are to be found. In many instances this is not problematic, but if materials become lost it suddenly becomes a huge issue. Thirdly, centralised PPC systems aggregate similar resources. Most factories have a number of machines which are similar but not exactly the same: machines differ in speed, quality range, changeover patterns, maintenance requirements, supervisory requirements and many other features. Finally, centralised PPC systems aggregate over materials. Small differences in material batches are ignored in material planning systems. These details are unmanageable in central planning systems. Nevertheless, these examples of aggregation are best practises in planning, and there is no obvious reason to change them.

Monitoring and control problems however seldom present themselves in aggregated terms. Manufacturing and distribution problems usually occur in real time, not far away in a future period. Materials mislaid in a warehouse or on the shop floor are missing now. Quality problems leading to the production of scrap are always related to a specific machine, tool or operator. Resource problems relate to specific equipment that is no longer available and maybe in need of maintenance. Material problems are related to a specific piece, pallet, batch or other unit of processing. These are specific problems that occur in detailed, disaggregated form. Therefore, it takes humans to estimate their impact on the aggregated plans.

Another issue stems from the fact that planners using a centralised PPC system typically adopt a hierarchical approach. This has the advantage that the complexity on the various organisational levels is reduced, with each level able to function partially independent. However, performance feedback is important in hierarchical systems for proper functioning [121]. Therefore, appropriate and timely feedback has to be provided by the lower levels to the higher levels. Furthermore, the higher levels need to be able to respond adequately and in time to this feedback. If any of these requirements are not met, it becomes impossible for planners to effectively monitor the plan's execution. This problem has been referred to as the vertical communication bottleneck in organisations [53]. Therefore, due to these issues, monitoring and control in the PPC context still largely relies on manual steps.

3.3.2 Problem statement

The fact that humans are needed to interpret problems in materials or equipment that have factory-wide consequences hampers further progress with PPC. Human expertise is generally not available around the clock, and humans have limited information processing capabilities. People cannot always know the exact manufacturing conditions and constraints in remote manufacturing facilities. When manufacturing problems are detected, they first have to be communicated and interpreted, then the PPC systems are notified and, finally, planners will react. Consequently, reaction to manufacturing problems by PPC systems and central planners is usually slow [194]. This analysis brings us to the initial problem statement:

- ➟ *Is it possible to design an automated monitoring and control system which works at the level of detail where problems typically occur and which can interpret these problems directly, then inform and propose solutions to the appropriate person (typically the shop floor supervisor) and, if necessary, provide feedback to PPC systems?*

3.3.3 Performance measures

The performance of PPC systems is generally studied in logistic and economic terms. Logistic performance measures include service levels of stock points, average lead times and due-date reliability. Economic aspects cover inventory levels, resource utilisation, overtime costs, profit margins etc. It is not easy to relate the performance of monitoring and control activities to such indicators. Therefore, the designed artefact described here will also be evaluated in terms of its impact on the robustness of the larger PPC system. The argument is that the more problems that can be handled locally without even being observed in the wider PPC context, the better the system performs. To achieve this, a monitoring and control system should prevent small disturbances having large consequences.

3.4 System architecture

This section describes the proposed architecture of a production monitoring and control system. First, the requirements are presented. Next, the main design properties of the proposed monitoring and control system will be described in greater detail.

3.4.1 Requirements for monitoring and control systems

As discussed earlier, centralised planning and control systems have problems in dealing with disturbances because they work with aggregated data. However, as disturbances seldom present themselves in aggregated terms, an effective monitoring and control system needs to work with data on the same level of detail as where the disturbances normally occur. This leads to the formulation of the first requirement:

- *Requirement 1*: The system should work with data on the same level of detail as where disturbances occur.

Furthermore, it was stated that feedback from the machine level to factory-level PPC systems has remained problematic. Therefore, a monitoring and control system should be able to provide useful feedback about disturbances to the appropriate person in order to enable efficient handling of the disturbances and, when required, communicate this feedback to the factory-level PPC systems. This leads to the formulation of the second requirement:

- *Requirement 2*: The system should be able to provide feedback about disturbances to the appropriate person directly when they occur and, if needed, communicate this feedback to the factory-level PPC systems.

By using detailed, real-time disaggregated data, the search space available for a suitable solution to a disturbance increases significantly compared to the current situation. However, the large amount of information in this space can make it difficult to manually find a suitable solution. Therefore, if a person is to adequately respond to the provided feedback in a timely fashion, the support of a system which can search this space effectively is required. This leads to the final requirement:

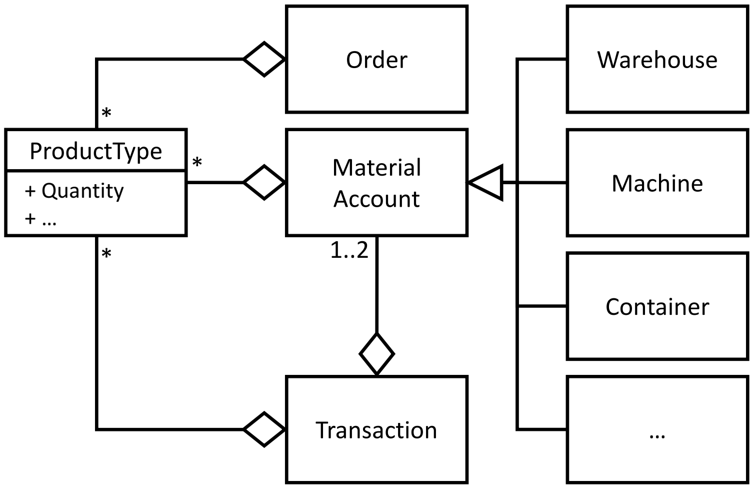
- *Requirement 3*: The system should be able to propose solutions to the appropriate person immediately when a disturbance occurs.

Below, it is explained how these requirements are incorporated in the system design, by applying the concept of intelligent products.

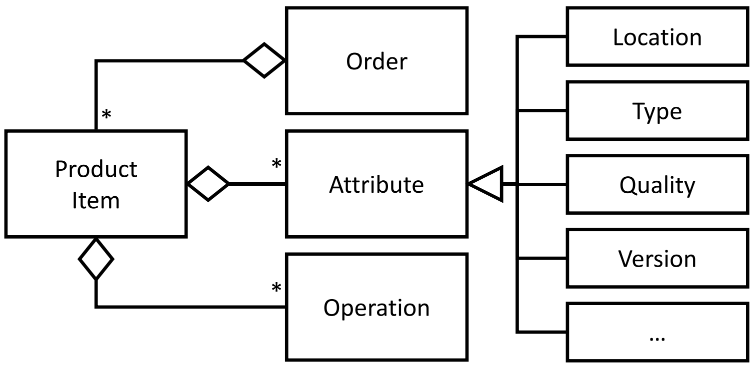
3.4.2 Structural design

Centralised PPC systems are generally inventory-based systems, built around material accounts and transactions between such accounts. Each account represents the quantity of a particular material in a specific location [146]. Such a location can belong to any warehouse or shop floor facility, or it can be a packing unit (e.g. a container or pallet) which can store material. A simplified UML class diagram of an inventory-based system is shown in Figure 3.2a. As shown in the figure, an inventory-based system keeps track of the number of units of each product type stored in every location by means of a material account. Further, through transactions, the number of products of a certain type at a specific location can change. The inventory-based system design shows that no information is stored about individual products [197]. This functionality of linking data to individual physical products is referred to as tracing, defined as the ability to preserve the identity of a particular physical product, as well as its complete history [184].

However, in order to meet *Requirement 1*, the monitoring and control system has to be able to store detailed information on the level at which disturbances occur. Therefore, tracing functionality has to be incorporated in the system design. Accordingly, a product-centric (rather than an inventory-based) system design is adopted. A typical UML class diagram of



(a) Inventory-based system



(b) Product-centric system

Figure 3.2: System designs

a product-centric system is shown in Figure 3.2b. As shown in the figure, the physical product item becomes a new entity in the system, replacing the product type entity which was associated with locations and transactions. In this new design, attributes such as location, type, quality and version can be stored for every individual physical product. Further, for each product, the physical operations through which it has been transformed into its current state can be stored. The location of each item can be more specific since there is no longer a need to aggregate over fixed locations. This approach enables monitoring and control on the level of individual products at which disturbances typically happen. It is important to note that this design assumes that the system has up-to-date information about all products, and that the system is able to detect irregularities in this information.

3.4.3 Product agent behaviour

In order to collect up-to-date information on all products, to be able to detect problems and provide feedback to the appropriate person, and to be able to propose solutions to these problems, some form of intelligence is needed. As discussed in Section 3.2, agents are considered the natural response to the need to implement the intelligence part of intelligent resources. Similarly, agents also seem best suited to implementing the intelligence part of intelligent products due to their knowledge and reasoning capabilities which can enable them to carry out most repetitive tasks. Therefore, in the system design proposed here, every product will have its own agent for performing these tasks. The behaviour of these product agents will be introduced below, according to the three levels of intelligence as distinguished in Chapter 2.

Level 1: Information handling

Firstly, product agents need up-to-date information. In order to execute its tasks properly, the most important information required by an agent consists of two parts: the current status of the product, and the planned or desired status of the product. Determining the desired status of the product is relatively easy, the agent can analyse information in currently applied PPC systems, such as order due dates and planned transactions and operations which will affect the product. However, determining the current status of the product can be more problematic. One approach is to re-examine the information already present in the current systems: this will reveal which transactions and operations have already been performed, and which still need to be performed. However, it is unlikely that this information will be sufficient since there may be delays between when a transaction is performed and when this is recorded in the system and, more importantly, the information will most probably be on a higher aggregation level. Therefore, in order to obtain up-to-date status information on individual products, auto-ID technologies, such as barcodes and RFID, will have to be introduced to uniquely identify individual products. Further, the location of a product can be approximated using various techniques [177]: monitoring by wireless and cellular access points, alterations to and triangulation of radio or ultrasonic signals, scene analysis, laser trackers, as well as micro-sensors and micro-electromechanical systems etc. Another frequently applied technique is to update the location status of a product each time its barcode or RFID tag is scanned provided the physical location of the scanner is known [77]. To gain more detailed status information about a product, identification and localisation technologies can be combined with sensor technologies, such as those based on thermal, acoustic, visual, infrared, magnetic seismic or radar systems [177]. All these techniques bring the Internet of Things to the shop floor.

Level 2: Problem notification

Provided the product agent has knowledge of the plan as well as the current status in terms of plan execution, it is enabled to detect disturbances as needed for meeting *Requirement 2*. To achieve this, the agent employs a mechanism, such as a utility function, to determine whether progress matches the schedule and whether other status properties are still within an acceptable range. Such utility functions can be based on factors such as the amount of time remaining to the order due date, whether there is a proper plan to finish the product on time, whether the plan execution is on schedule, plus factors such as whether the product is within the desired temperature range. If an agent's utility score drops below a certain threshold, the agent will enter a problem state, and can immediately provide feedback about the problem to the appropriate person who then knows which precise products on the shop floor are currently having problems. Moreover, if needed, feedback about the problems can also be communicated to the factory-level PPC systems.

Level 3: Decision making

Besides providing feedback on problems, it is beneficial if the agents propose solutions or suggest how to reduce the severity of the problem. As a result of the continuous information gathering, all agents are aware of the current situation. This enables the agents to negotiate in real-time about alternative plans to overcome the disturbance. However, it will not be feasible to let each product agent negotiate with all other product agents, especially when the number of products is high. Therefore, an auctioning approach based on the Contract Net Protocol [167] is proposed, one in which factory resources, such as machines, can offer their capacity, and product agents can bid for this capacity. The overall result of the negotiations between resources and product agents will be presented to the appropriate person who can then decide whether or not to schedule the tentative actions. If the person does not agree with parts of the schedule, changes can be proposed in such a way that the agents can learn new preferences from them. In this way, *Requirement 3* can be met. This approach is similar to the Escape and Intervention monitoring and control mechanism proposed by Roest and Szirbik [147].

The proposed system architecture was evaluated by means of simulation experiments, through the development of a prototype implementation. A thorough elaboration on these experiments and the results can be found in Chapter 4.

3.5 Conclusions

In this chapter, the following has been concluded:

➟ Improving monitoring and control activities has received much less academic attention than improving planning activities.

➟ During production, many different kind of disturbances can occur, leading to deviations from the original plan.

➟ Centralised production planning and control systems have drawbacks concerning monitoring and control, with respect to the many small disturbances that occur during plan execution.

➟ Intelligent products appear to be a new and promising approach for dealing with these disturbances, as when disturbances happen, the intelligent products can directly investigate all available information, inform the planners if needed, and propose solutions to reduce the severity of the problems caused by the disturbance.

➟ A novel architecture for a production monitoring and control system based on the concept of intelligent products is presented.